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A PRACTICAL ELECTRONIC INSTRUMENTATION COURSE FOR ENGINEERING STUDENTS

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ABSTRACT

A course on Electronic Instrumentation has recently been developed at the Universidad Autonoma de Madrid (Spain), which specifically emphasizes practical aspects. The objective of the course is to link theoretical principles with practical issues of electronic instrumentation through the development of a final project. First, students take practical work in several different scenarios, which are the basis for the design of an engineering project aimed to solve an electronic instrumentation problem which is set by the students. Students are exposed to a set of multidisciplinary aspects, both theoretical and practical, providing them with the ability of integrating blocks in which they have practically worked into a full instrumentation project. The course provides not only enhanced academic training but also increased student motivation, as students are encouraged to propose their own projects.

Key-words: electronic instrumentation, practical approach, correlation theory-practice, student evaluation.

1. INTRODUCTION

One of the fundamentals of the technological progress in the field of electronic instrumentation is the need for practical training as an essential part of the learning activity. The process of engineering generally consist of the following sequential activities [1]: i) conceive, ii) experiment, iii) design, iv) build, v) test, and vi) improve. In most of these activities, practical aspects are crucial. It is therefore necessary an exposure to these aspects, in order to make electrical and electronic engineering graduates more employable and productive when they enter industry. However, although the resources present in a typical engineering laboratory usually cover isolated blocks of a whole project, it is desirable that the students develop the abilities to integrate blocks of a project in which they have practically worked. This interest is motivated by many aspects and manifests at many levels, from the technical structure of the final product to as an element of the development scheme. Unfortunately, resources present in an electronic instrumentation laboratory are not always enough to guarantee the acquisition of the abilities to accomplish such integration process, especially aimed at industry engineering work.

With these ideas in mind, a course on Electronic Instrumentation has been developed at the Universidad Autonoma de Madrid, which is a mandatory subject of the last course of the M.Sc. in Telecommunication Engineering. The goal of the course is not only to provide students with the theoretical principles, but also to link them with the practical aspects of electronic instrumentation. First, the students take practical work in the technical abilities of the electronic instrumentation course in several different scenarios, using the available hardware at the laboratory. The objective of yielding awareness about the whole project is achieved by means of simulated case studies, which are designed by the students, and which include the hardware used in the laboratory as a critical part.

In this paper we describe the particulars of this course, highlighting his objectives and contributions, and we will analyze whether the practical implementation proposed indicates a successful achievement of the proposed objectives. The course has been successfully developed and taught to 40 students from February to May 2009. Results presented in the paper illustrate the relationship about the scores obtained by the students in theoretical and practical work, and also presents experiments comparing the scores in each of the modules of the proposed practical methodology proposed. There are also included the results of the final student official opinion polls that are conducted at Universidad Autonoma de Madrid every academic year. Outcomes have been satisfactory, showing that students are satisfied with the course, and more motivated since they are allowed to take active role in the design and experimentation of an electronic instrumentation system.

This paper is organized as follows. In Section 2, we highlight the motivation, objectives and contributions of the proposed methodology. The organization of the course is described in Section 3, including details of the practical sessions and of the evaluation methodology. Results of the course implementation are included in Section 4, giving details of the marks obtained by the students and the results of the student opinion polls. Conclusions are finally given in Section 5.

2. MOTIVATION, OBJECTIVES AND CONTRIBUTIONS OF THE PROPOSED METHODOLOGY

Modern electronic instrumentation requires broad knowledge of a multidisciplinary approach [2]. It is therefore fundamental that the students face problems not only related to the implementation of electronic instrumentation systems, but also to the integration of such implemented modules among an industrial development chain. The objectives of the course are therefore adequate to this principles. After completing the course, the students should be able to do the following:

- Understand the principles of electronic instrumentation.
- Understand the main specification of a measuring system.
- Utilize a PC-based hardware that provides interaction with external signals, sensors and devices.
- Design simple measuring systems and micro-controller-based applications.
- Learn to integrate hardware instrumentation modules into a full instrumentation project.

The resources needed to accomplish the first four objectives can be provided by the typically available resources in a laboratory at the university, and at a reasonable cost. However, the last objective is costly, since it implies the availability of a full industrial system in which the modules developed at the laboratory should be integrated. This exceeds the budget that many universities dedicate to teaching laboratories.

The accomplishment of all the objectives described, including the last one, motivates the organization of practical work proposed in this paper, which constitutes the main contribution of the proposed methodology. The idea is to divide the practical working time (15 hours) into four different sessions. The first three sessions consider the implementation of several hardware modules which can be developed with the available equipment at the laboratory. The last session is a case study proposed by the students under determined guidelines, where an engineering project is proposed considering the hardware modules developed. This last session will not be finally implemented, since it consists of a full engineering problem, but their specification must be detailed and all the proposed blocks of the project have to be described with the required level of an engineering project. Figure 1 summarizes the proposed methodology.

With the proposed course, students not only supplement their academic training in electronics, but also gain experience in applying theoretical knowledge to the resolution of practical problems.

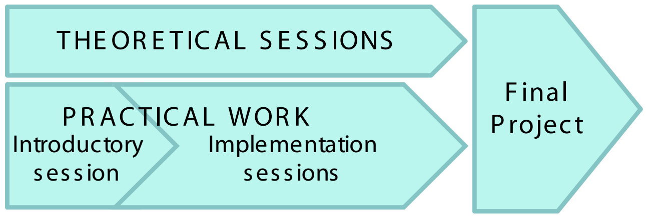

Fig. 1. Proposed practical methodology, which is the main contribution of the course.

Theoretical topics

1. General Principles of Instrumentation.
2. Statistical Error Analysis.
3. Electronic Instrumentation Amplifiers.
4. Analog-Digital Conversion.
5. Measurement of Physical Magnitudes.

Laboratory sessions

1. Introduction to Laboratory Hardware.
2. Thermometer Using the Analog-to-Digital Converter.
3. Dusk Indicator Using the Voltage Comparator.
4. Brushed DC Speed Control with Optical Encoder Feedback.
5. Engineering Project.

Table 1. Syllabus of our Electronic Instrumentation course.

3. ORGANIZATION OF THE COURSE

The organization of the course is summarized in the Syllabus presented in Table 1. The four-month course provides 4.5 lecture credits (45 hours in the current Spanish system) and 1.5 laboratory credits (15 hours in the current Spanish system). A set of laboratory sessions complement the theoretical training and a final design project is used to assess the practical knowledge acquired by students.

The required skills the students may have to take advantage of the course and achieve its objectives are as follows. It is recommended that students have passed previously other subjects on Circuits and Electronics, Circuit Analysis and Design, Signal Processing, Digital Systems and Programming (including assembly code). Therefore, it is intended for students with a previous background and skills in electronics.

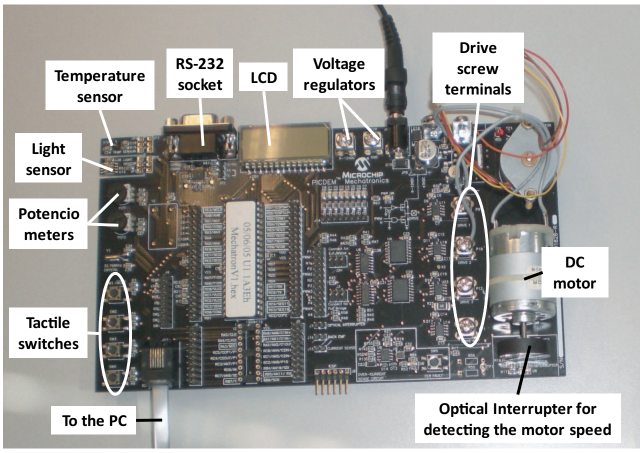

Fig. 2. Photograph of the PicDem development board from Microchip (TM) used in the laboratory practicals.

3.1. Theoretical Sessions

Theoretical sessions are mainly based on lectures which cover the topics included in Table 1 (top). These topics are typical in modern electronic instrumentation, and there is plenty of bibliography available. We have used mainly [3], which has proven to be an extremely useful resource for the course. Other useful references, recommended for the students were [4, 5].

3.2. Practical Sessions

Methodology

The practical methodology sketched in Figure 1 is developed as follows. The first introductory session and the subsequent three units in Table 1 are small projects where the students have to implement several functionalities using the available hardware of the lab.

The hardware used in the whole course is the so-called PicDem development board from Microchip (TM) (Figure 2), which is a platform to handle several electronic sensors (including a temperature, light and optical encoder sensor) and other devices (engines, light emitting diodes, etc.) using a PIC microcontroller. The software used to control the board is the MPLAB (TM) IDE [6], which runs on a Personal Computer (PC). Since it is running as software on the PC, it has complete information about the internal state of the microcontroller at each instruction (memory areas, register, peripherals, etc.), allowing real time monitoring.

The software includes several demonstration programs covering basic tasks such as reading a sensor, interfacing to a LCD and driving a motor. These projects also provide examples of how to use the various peripherals of the card. We have organized the laboratory sessions so that they are based on the use of these projects. The projects are of increasing difficulty, allowing to build knowledge as students progress from one project to the next. The assembly source code has comments with allow to identify relevant steps, so students are able to monitor the execution although they are not familiar with the specific programming language. This avoids tieing students to a manufacturer-dependent solution, which is quire important in such a changing technological field [2]. At the same time, students do not have to invest time on learning specificities of the particular micro-controller which, in all probability, will be different to those that they will find in their respective job positions.

Sessions Organization

The students are organized in teams of a maximum of 2 members, and they work together to accomplish the objectives in each of the laboratory sessions. Each session lasts 2 hours and the sessions are organized considering that the amount of work needed exceeds the 2 hours available, therefore a substantial amount of work should be performed by the student outside the session. The sessions and the main expected results are described as follows (see Table 1, bottom):

1. Introduction to Laboratory Hardware. The hardware used in the laboratory (PicDem board) and the PC-based interface (MPLAB (TM) IDE) is described, with the aim of serving as an interface for the students to start interacting the system.

2. Thermometer Using the Analog-to-Digital Converter. A thermometer is implemented using the temperature sensor in the PicDem. Then, the static transfer function of the thermometer is measured, taking different references of various reliability. The aim is to highlight the importance of a proper calibration process, as well as to let the students learning to work with analog-to-digital converters (ADC) and conditioning circuits. This covers several of the theoretical aspects of the course (theoretical topics 1, 4 and 5 in Table 1).

3. Dusk Indicator Using the Voltage Comparator. A dusk indicator is implemented using the light sensor of the PicDem. Using the PC-based interface, the charactersitics of the components are measured (sensor, comparator). The need of hysteresis in the whole process is analyzed and a hardware alternative for its implementation is theoretically derived. This session covers part of theoretical topics 1, 2 and 5 in Table 1.

4. Brushed DC Speed Control with Optical Encoder Feedback. A DC motor is controlled by the use of the optical encoder present in the PicDem board. The characteristics of the motor and the PicDem are measured and documented using the PC-based interface. Moreover, the circuit used to feed the motor (Pulse Width Modulation circuit included in the PIC of the board) is also characterized. Finally, the static transfer function

relating speed to input voltage is estimated under several situations, leading to a complete understanding of the system under analysis. This sesison covers part of theoretical topics 1, 2, 4 and 5 in Table 1.

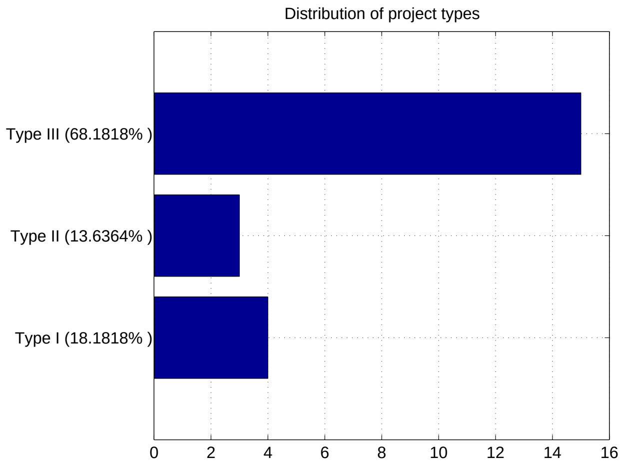

Fig. 3. Distribution of project types (I, II and III with increasing difficulty) among different teams of students for the laboratory session 5 of the proposed practical methodology.

Engineering Project

The main contribution of the proposed methodology is the existence of a final project (lab session 5 in Table 1) whose aim is to integrate part of the developed modules in previous sessions into a full engineering project. Thus, in this last session students are asked to design an engineering project to solve an electronic instrumentation problem which is set by themselves. The main condition of the project is the use of the laboratory hardware as a critical component. The proposed work methodology considers the following steps:

- **Identification of an engineering problem** where electronic instrumentation will play a fundamental role. For this section, the students must be creative in applying all the concepts acquired in the theoretical sessions, also considering the modules implemented in previous practical sessions. Aspects to evaluate are the potential difficulty and the originality of the problem.

- **Identification of the components** needed to solve the instrumentation problem in the form of an engineering project. In this section, not only the components have to be specified, but also their relationship with the available hardware, namely PicDem (Figure 2). The level of detail to be specified is maximum, with the requirement of finding technical sheets for each component, and also to explain it deeply in order to integrate it in the whole project. The components may be PicDem components (either used in previous sessions or not previously explored at all) or other external components. The evaluation of this step will be based on the difficulty to find the specified components, the technical adequacy of them to the problem, the performance with respect to other options in the market and the level of detail of their description (technical sheets and additional information).

- **Engineering project.** Here the student should give a solution to the proposed problem in the form of an engineering project. It is not a requirement to make the programming routines for PicDem operation in assembly code, but the pseudo-code of its operation should be included. Schematics, diagrams and detailed descriptions of the solution adopted with a clear explanation of the relationship among components and with the problem to solve are also required. In this section the evaluation will be based on the quality of the schematics and diagrams, the adequacy of the project to the problem to solve, the quality of the explanations and the implementability of the designs and solutions adopted.

Several types of possible projects are proposed to the students, which serve as guidelines to their development. Each type of project presents an increasing difficulty which allows students to quantify the relevance of the problem presented and the solution adopted. The proposed project types and their characteristics are specified here:

1. **Type I Project.** This project basically consists of improving one of the modules implemented in previous sessions in order to give solution to the problem proposed by the students. No internal or external component is required. This project is the easiest of all, which is considered in the evaluation (see Section 3.3).

2. **Type II Project.** This project considers two alternatives: $i)$ the project includes other components of the PicDem not used in previous sessions; or $ii)$ the project includes other components external to the PicDem. Given the difficulty of searching, analyzing and specifying components not seen before, the evaluation of this project is more favorable than in the Type I (but less than the Type III, see next).

3. **Type III Project.** In this project, both components of the PicDem not used in previous sessions and other components external to the PicDem are used. Given the difficulty of searching, analyzing and specifying components not seen before, the evaluation of this project is the most favorable of all the proposed Types.

3.3. Evaluation

As it happens in the Spanish education system, the evaluation of a course is given in a $[0, 10]$ interval, being 0 the minimum

Type I

- Measurement of Light Time.
- Motor Control by Temperature Sensor.
- Motor Control by Temperature Sensor.
- Motor Control by Temperature Sensor and Speed Measurement.

Type II

- Control of a Window Blind by Light Sensor.
- Domotic Control of a House.
- Motor Control by Temperature and Light sensors, and Switches.

Type III

- Automation of a Lighthouse.
- Control of a Canopy by Humidity and Light Sensors.
- Hold-on Time Control for a Bus Line.
- Measurement of Glucose Level.
- Motor Control by Strain Gauges.
- Obstacle Map Design.
- Simulation of Inhabited House.
- Smoke Detector.
- Stability Control of a Car.
- Temperature and Humidity Measurement and Registry.
- Temperature Controller.
- Temperature Measurement and Registry.
- Turbo-Engine Pressure Control by Solenoid Valve.

Table 2. Project titles grouped by project type.

score and 10 the maximum score, and considering that a student passes an exam when his/her score is greater or equal than 5. The evaluation of the whole Electronic Instrumentation course was given by the following formula, derived from the current rules at Escuela Politecnica Superior at Universidad Autonoma de Madrid:

$$FS = 0.25 \times PS + 0.75 \times TS \qquad (1)$$

where FS is the final score of the course, TS represents the score obtained in the evaluation of the theoretical work and PS is the score of the practical work. As additional constrains, it must happen that both $TS \geq 5$ and $PS \geq 5$, meaning that the student has to demonstrate his attitudes both for theoretical and practical work.

The theoretical score TS is obtained from an exam where the knowledge acquired in theoretical sessions is evaluated. The exam encompasses a closed-answer test (30% of TS) and some design problems to solve (70% of TS). For this exam, according to the Spanish law, a student can attend two times per year. If they do not pass the first call (in June) they can attend to the second call.

The criteria for evaluation of all the practical part of the course has been transparent in all moment, with the students being informed of it conveniently from the beginning. The score PS is computed as follows:

$$PS = 0.20 \times S_2 + 0.20 \times S_3 + 0.20 \times S_4 + 0.40 \times S_5 \qquad (2)$$

where S_i is the score obtained in laboratory session i as it is enumerated in Table 1 (bottom). It can be noticed that laboratory session 1 is not evaluated, because it is an introductory session. Moreover, the project represent almost half of TS, representing the emphasis that the practical methodology of the course presented in this paper puts in the integration of modules into a full engineering project.

For the evaluation of the engineering project (laboratory session 5 in Table 1) the project types (Type I, II and III, see Section 3.2) has an influence in the final qualification. The idea followed is that the more difficult the project, the more difficult will be to achieve a higher score. However, there is the opportunity of achieving the highest score with all the project types if the quality is sufficiently high. Thus, a correction factor has been imposed to the score obtained in laboratory session 5 depending of the project type that the students have selected. In this way, Type III projects would tend to obtain the highest scores, whereas Type 1 projects will tend to obtain the lowest scores.

4. RESULTS

The results presented here are interpreted over a sample of 40 students of the last course of Telecommunication Engineering at Universidad Autonoma de Madrid. Since the students are

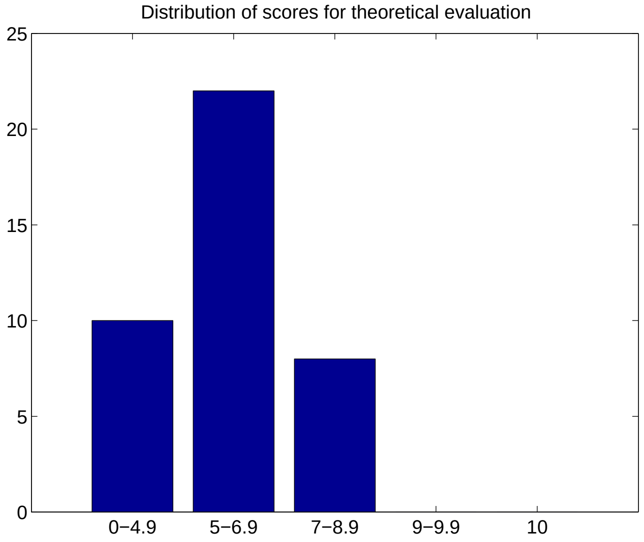

Fig. 4. Histogram of theoretical scores TS following the Spanish evaluation system (from 0 to 10). 40 students analyzed.

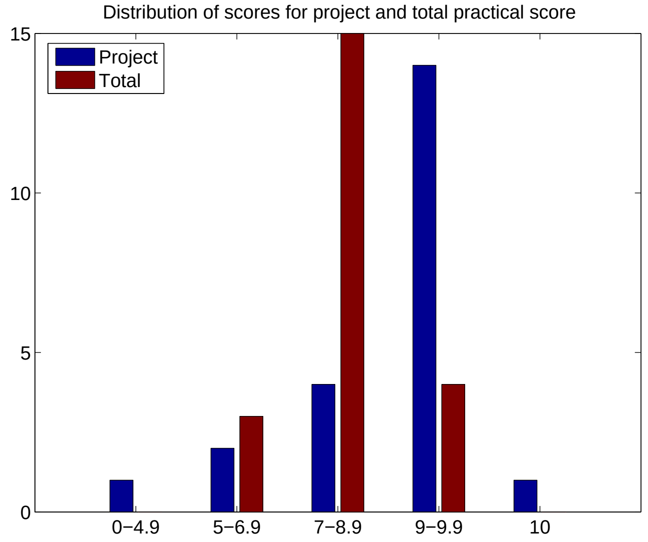

Fig. 5. Histogram of practical scores PS and scores for the proposed project S_5 following the Spanish evaluation system (from 0 to 10). 22 teams analyzed.

organized into teams of maximum 2 people for practical laboratory work, the sample reduces to 22 teams for the analysis of the outcomes from the practical part of the subject. Also, since 2009 was the first year in which the proposed methodology is implemented, the sample cannot be compared in time. This is proposed as future work of this contribution.

4.1. Project type distribution

Distribution of project types among teams in the selected sample is shown in Figure 3. It is shown that the students have mainly selected Type III projects, which are much more difficult to develop. This is an indication of the degree of motivation of the students with respect to the proposed methodology. Moreover, given the transparency in the evaluation methodology followed, such distribution means that the students are ready and willing to explore and deeply specify components not seen before, and to integrate it into an engineering process. This is an indicator that the knowledge acquired in the theoretical-practical methodology followed seems sufficient for them in order to accomplish the objectives of the project.

Table 2 lists all the titles of the projects, classified by project type. It is observed that the originality of the project title depends on the type of project, being Type I projects much more typically seen than Type III projects.

4.2. Scores

The scores obtained in the theoretical subject (TS scores) are represented in Figure 4. it is observed that the scores concentrate in the 5 to 8 region, not being higher than 9 in any case. This is an indicative that, although the vast majority of the students pass the exam ($TS \geq 5$), obtaining the maximum score (10) is extremely difficult. This has been the trend in Spanish evaluation methodologies over decades.

Figure 5 shows histograms with the distribution of the scores obtained in the practical part of the course, compared to the score obtained in the proposed project (laboratory session 5). It is observed that, in general, the scores in the practical part of the course are significantly higher than in the theoretical part of the course (compare with Figure 4). This was a design requirement, since the challenge of practical sessions should be kept while fostering the student's motivation. Moreover, in general it is observed that the trend of the scores in the proposed project is much higher than the total score. That means that, despite the intrinsic difficulty of an engineering project, the students have taken the initiative to accomplish it in a successful way. Figure 6 shows the distribution of scores for each of the sessions in the practical part of the course, namely S_2, S_3, S_4 and S_5. These results confirm this trend, showing a remarkable improvement in the score obtained by the students with the number of laboratory session.

Correlation between theoretical knowledge acquired and practical competencies is shown in Figure 7. It is observed that the correlation coefficient among the theoretical score (TS) and the practical score (PS) is positive, and having a non-negligible value of 0.32 from a maximum of one. That indicates that the theoretical knowledge gained by the students is in relation to the practical abilities achieved, which fulfills part of the objectives of the course. This is also seen in Figure 8. if we obtain the correlation between the theoretical score and the proposed project (laboratory session 5).

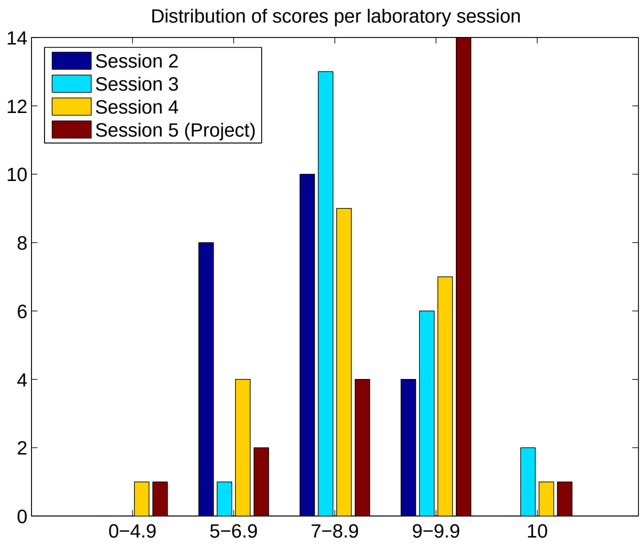

Fig. 6. Histogram of practical scores for all the laboratory sessions following the Spanish evaluation system (from 0 to 10). 22 teams analyzed.

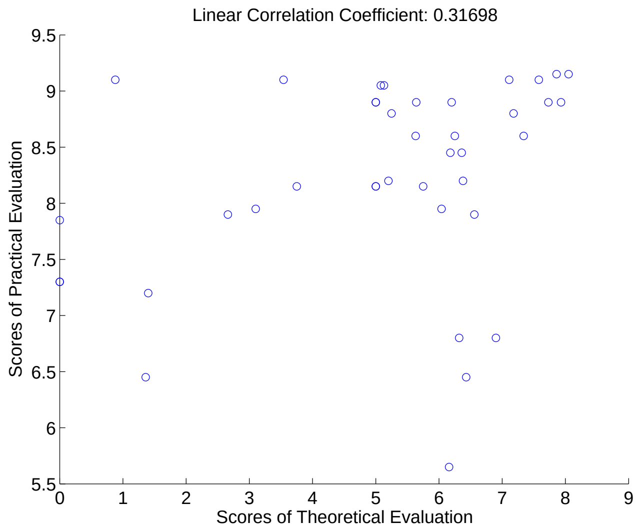

Fig. 7. Scatter plots showing correlation between theoretical scores (TS) and practical scores (PS). Correlation coefficient is also shown. 40 students analyzed.

Again, the correlation is positive, and the coefficient has also a non-negligible value, in this case of 0.25, indicating that the objective of the proposed project of yielding practical and theoretical abilities to students to solve electronic instrumentation problems has been achieved.

4.3. Official student opinion polls

Figure 9 shows the results of the official polls conducted by Universidad Autonoma de Madrid, illustrating the opinion of the students about their work in the laboratory. The aspects evaluated are the following:

1. Clarity of concepts.
2. Organization.
3. The teacher dominates the subject.
4. Availability of the teacher in case of doubt.
5. Receptive and friendly attitude of the teacher.
6. Regularity of assistance.
7. Punctuality.
8. **General opinion about the laboratory.**

The results of such polls are extremely satisfactory, over the mean value of the same school and university. That indicates that, although such results do not refer strictly to technical topics, the laboratory has been worthy for the students, and their degree of satisfaction is excellent.

5. CONCLUSIONS

The design of modern electronic instrumentation requires broad knowledge and a multidisciplinary approach, as reflected in the structure of this course. A final design project is used to link theoretical principles with practical issues of electronic instrumentation, so that they acquire the ability of integrating blocks in which they have practically worked into a full instrumentation project.

Outcomes have been extremely satisfactory. Students enhance their academic education, are more motivated, play an active role in project design and receive crucial pre-career exposure to practical aspects. Among the different types of possible projects, students go for the more difficult to develop, which is an indication of the degree of motivation of the students with the proposed methodology. Distribution of marks show an increasing tendency with the number of laboratory session, indicating a correct progress of the students throughout the course. Finally, results of the opinion polls carried out at the University show an excellent degree of satisfaction by the students.

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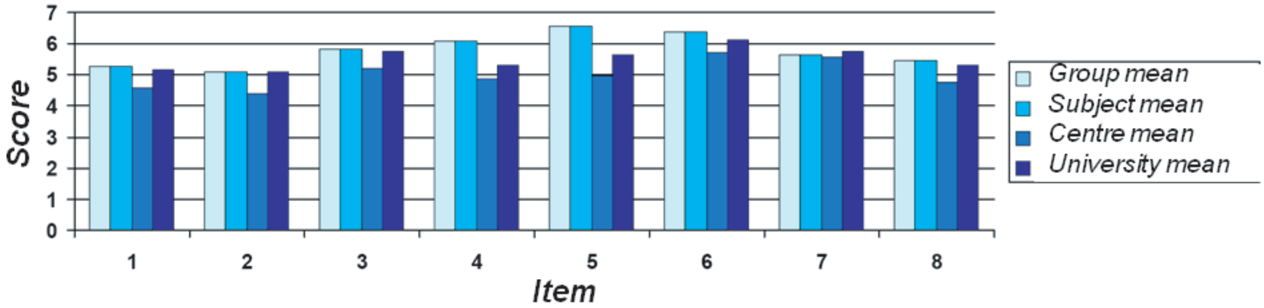

Fig. 9. Results of the official student opinion polls for the practical part of the course.

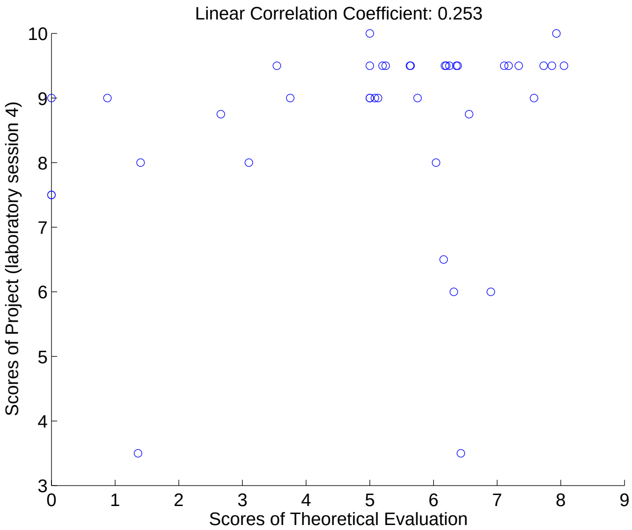

Fig. 8. Scatter plots showing correlation between theoretical scores (TS) and scores for the proposed project (S_5). Correlation coefficient is also shown. 40 students analyzed.

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